International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 6 June 2022, pp: 1042-1046 www.ijaem.net ISSN: 2395-5252

A Ride Comfort Performance Analysis of Semi-Active Hydraulic Isolation System of Earth-Moving Machinery Cab using Fuzzy Logic Control

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Submitted: 01-06-2022 Revised: 10-06-2022 Accepted: 15-06-2022

ABSTRACT:To improve the ride comfort of the earth-moving machinery cab, a semi-active hydraulic isolation system is proposed and analyzed the ride comfort performanceof its compared with the passive hydraulic isolation system. A half-vehicle dynamic model of a wheel loaderis established under the different operating conditionsand a fuzzy logic controlleris designed for control of the damping coefficient of a semi-active hydraulic cab isolation system for a wheel loader.The ride performance of semi-active hydraulic cab isolation system is evaluatedunder the different movement conditions. The comparison results indicate that the proposed controller for semiactive cab hydraulic isolation system has the significantly improved vehicle ride comfort in comparedwith passive hydraulic cab isolation system under large amplitude and low frequency excitations.

KEYWORDS:Wheel loader, Cab, Passive hydraulic isolation system, Semi-active hydraulic isolation system, Ride comfort.

I. INTRODUCTION

Unlike vehicles designed primarily for transport, the wheel loader is built without any axle suspension system. The front wheels are attached directly to the vehicle body, and the rear axle is allowed to oscillate around the longitudinal axis, thus allowing all wheels to maintain contact with the ground. Wheel loaders are usually operatedunder the harsh environmental conditions.Wheel loader drivers are often exposed to high levels of whole body vibration. In short-term perspective these vibrations will affect operator comfort negatively and cause driver fatigue.A multibody dynamic model of a compact wheel loader was createdproposed and analyzedin the reference [1] which was verified by comparing the calculated results with the ground test results. Accordingly, the influence of whole-body vibration in heavy equipment operators of a front-end loader was analyzedin the reference [2]which have focused on role of task exposure and tire configuration with and without traction chains. Two standards such as ISO 2631-1(1985) and ISO 2631-1 (1997) were used to assess the effect of wheel loader vibration on vehicle ride comfort [3]. However, the overall total values of vibration measured on the wheel loader in all operations exceeded the ‘uncomfortable’ boundary specified in two standards. Then, limited studies were carried out to evaluate the whole-body vibration (WBV) exposure experienced by operators of compact wheel loaders (CWLs) according to ISO 2631-1:1997 [4]. In order to find abnormal vibration components, the order tracking technique (OTT) and transmission path analysis (TPA) were used to evaluate the vibration sources of the wheel loader based on market feedback, the driver seat vibration of a type of wheel loader in the left and right direction [5] which was found to be significant over a certain speed range. The wheel loader suspension system was especially concerned by the researchers [10]. Three different layouts of hydropneumatic suspension namely unconnected strut (UCS), interconnected in roll plane (IC-R) and interconnected in roll and pitch plane (IC-RP) were installed on the wheel loader to improve vehicle ride comfort.However, the vibration response was still very high according to the standard of ISO 2631-1, thus, it was uncomfortable for operators to control the wheel loader on the roadworks. Nowadays, the control methods, such as Neuro-Fuzzy control with the fuzzy rules were successfully applied [7]. It was shown that suspension with control can significantly enhance the ride comfort compared with the passive suspension. Thus, the cab's isolation system was one of the most important factors to improve the vehicle ride comfort [8], cab comfort of excavators can be improved by changing the cab design (including dimensions, ingress/egress), view, reliability, and climate control.The study for controlling the damping force or coefficients of the cab isolation system had been concerned [9].

The proposal of this study is to analyze the ride comfort performance of semi-active hydraulic isolation system (SHIs) compared with the passive hydraulic isolation system (PHIs)of wheel loadercab usinga half-vehicle dynamic model. A fuzzy logic controller is designed for control of the damping coefficient of a semi-active hydraulic isolation system for the wheel loader cab. The ride performance of semi-active hydraulic isolation system is analyzed and compared with PHIs under the different movement conditions.

II. HALF –VEHICLE DYNAMIC MODEL OF A WHEEL LOADER

A half-vehicle dynamic model of a wheel loader with 6 degrees offreedom is establish to analyze the ride comfort performance of semi-active hydraulic isolation system (SHIs) compared with the passive hydraulic isolation system (PHIs), as shown in Fig. 1.

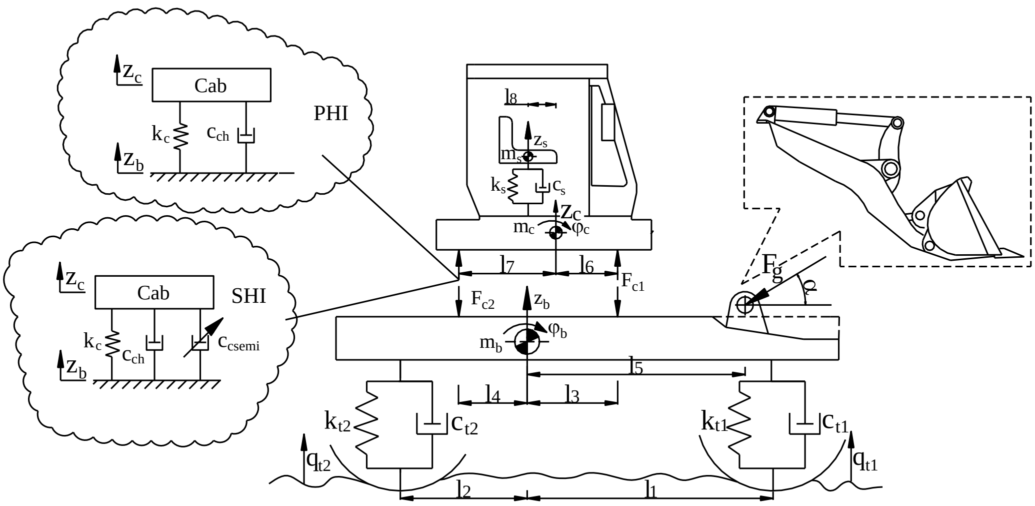

Fig. 1. Half-vehicle dynamic model of wheel loader

In Fig. 1, z_s, z_c and z_b are the vertical displacements of driver'sseat, cab, and vehicle body, respectively; φ_c, φ_b are the angular displacementsof cab and vehicle body, respectively; m_s, m_c and $m_b$are the masses of driver's seat, cab and vehicle body, respectively;k_s and c_s are the stiffness and damping coefficients of driver's seat suspension system respectively; k_{ti} and c_{ti} are the stiffness and damping coefficients of tires respectively; k_c and c_{ch} are the stiffness and damping coefficients of PHI, respectively; c_{csemi} is the damping coefficient of SHI; q_{ti} are the road surface roughness excitations; F_{ci} are the vertical forces of cab's mount system; F_g is an equivalent alternative force of a front mounted lifting implement, $l_k$are the distances (i=1÷2, k=1÷8).

The multi-body system theory is used to separate the system into subsystems which are linked by the force and moment equations. D'Alembert's principle is used to set up force and moment equations to describe vehicle dynamic subsystems. The equations of motion of Fig.1 can be written as

$$\begin{cases} m_s\ddot{z}_s = -F_s \\ m_c\ddot{z}_c = F_s - F_{c1} - F_{c2} \\ I_c\ddot{\varphi}_c = F_{c1}l_6 - F_{c2}l_7 - F_t l_8 \\ m_b\ddot{z}_b = \left[F_{c1}+F_{c2}\right] - \left[F_{t1}+F_{t2}\right] + \mathrm{F_g}\sin\alpha \\ I_b\ddot{\varphi}_b = F_{t1}l_1 - F_{t2}l_2 - F_{c1}l_3 + F_{c2}l_4 - \mathrm{F_g}\sin\alpha.l_5 \end{cases} \tag{1}$$

where, F_{ti}, F_{ci}, F_s and F_g are the vertical forces of tires, cab's mount system and the equivalent alternative force of a front mounted lifting implement, respectively which are determined by the formulas below.

The vertical forces of tires are determined below

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$$F_{ti} = k_{ti}\left(z_{t0i} - q_{ti}\right) + c_{ti}\left(\dot{z}_{t0i} - \dot{q}_{ti}\right) \quad (2)$$
$$= k_{ti}\left[z_b + (-1)^i \varphi_b l_i - q_{ti}\right] + c_{ti}\left[\dot{z}_b + (-1)^i \dot{\varphi}_b l_i - \dot{q}_{ti}\right]$$

The vertical forces of cab's mounts are determined below

$$F_{ci} = k_{ci}\left[z_c + (-1)^i \varphi_c l_{i+5} - z_b - (-1)^i \varphi_b l_{i+2}\right] + c_{chi}\left[\dot{z}_c + (-1)^i \dot{\varphi}_c l_{i+5} - \dot{z}_b - (-1)^i \dot{\varphi}_b l_{i+2}\right] \quad \text{Passive}$$
$$F_{ci} = k_{ci}\left[z_c + (-1)^i \varphi_c l_{i+5} - z_b - (-1)^i \varphi_b l_{i+2}\right] + c_{ci}\left[\dot{z}_c + (-1)^i \dot{\varphi}_c l_{i+5} - \dot{z}_b - (-1)^i \dot{\varphi}_b l_{i+2}\right] \quad \text{Control}$$
$$+ c_{semi}\left[\dot{z}_c + (-1)^i \dot{\varphi}_c l_{i+5} - \dot{z}_b - (-1)^i \dot{\varphi}_b l_{i+2}\right] \quad (3)$$

The vertical force of driver's suspension system is determined below

$$F_s = k_s(z_s - z_{so}) + c_s(\dot{z}_s - \dot{z}_{so}) = [k_s(z_s - z_c - \varphi_c l_c) + c_s(\dot{z}_s - \dot{z}_c - \dot{\varphi}_c l_c)] \quad (4)$$

The equivalent alternative force of a front mounted lifting implement is determined below

$$F_g = m_f g \quad (5)$$

where, m_f is the mass of a front mounted lifting implement

Road surface excitation: The road profile of the road surface roughness can be determined by the experimental formula [12]:

$$G_q(n) = G_q(n_0)\left(\frac{n}{n_0}\right)^{-\omega} \quad (6)$$

where $G_q(n_0)$ is the displacement power spectral densit (PSD) for the roughness of the road; n0=0.1 m^{-1} is a reference spatial frequency, ω=2 is the frequency index which determines the frequency configuration of the PSD of the road surface. Road surface roughness is assumed to be a zero-mean stationary Gaussian random process. It can be generated through an inverse Fourier transformation:

$$q(t) = \sum_{i=1}^{N} \sqrt{2G_q(n_i)\Delta n}\cos\left(2\pi n_k t + \varphi_i\right) \quad (7)$$

where N is the number of intervals, Δn = 2π ⁄ L with L as the length of the road segment, $\varphi_i$is a random phase uniformly distributed from 0-2π.

III. FUZZY LOGIC CONTROLLER DESIGN FOR SHI

Fuzzy logicwas initiated in 1965 by Lotfi A. Zadeh, professor for computer scienceat the University of California in Berkeley. In this study, Fuzzy logic-based control for semi-active hydraulic isolation system (SHIs) of a wheel loader cab is suggested and the capabilities for the improvement of ride comfort are studied through the software simulation. The relative displacement $z = (z_c - z_b)$ and the relative velocity $\dot{z} = (\dot{z}_c - \dot{z}_b)$ are considered as two input variables while the damping coefficient of SHI, c_{csemi} is the output of the fuzzy control. The nine value of the linguistic variables of input/output signals are defined by the positive very big (PVB), positive big (PB), positive medium (PM), positive small (PS), zero (Z), negative small (NS), negative medium (NM), negative big (NB), negative very big (NVB).The rules of "if-then" are used to define the relationship of z , $\dot{z}$ and c_{csemi} according to the designers' knowledge and experience, the fuzzy controller has all 81 possible rules listed in Table 1.Mamdani's fuzzy inference system is used to control SHIs ofa wheel loader cab.

Table 1. Rules for fuzzy control

c_{csemi}		z								
		NVB	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**	**PVB**
$\dot{z}$	**NVB**	ZE	PVB	PM	PS	ZE	NS	NS	NM	NM
	NB	NM	ZE	PB	PS	ZE	NS	NM	NM	NM
	NM	NVB	NB	ZE	PM	ZE	NM	NM	NM	NB
	NS	NVB	NVB	NVB	ZE	ZE	NM	NB	NB	NB
	ZE	NVB	NVB	NVB	NVB	ZE	NVB	NVB	NVB	NVB
	PS	NB	NB	NB	NM	ZE	ZE	NVB	NVB	NVB
	PM	NB	NM	NM	NM	ZE	PM	ZE	NB	NVB
	PB	NM	NM	NM	NS	ZE	PS	PB	ZE	NM

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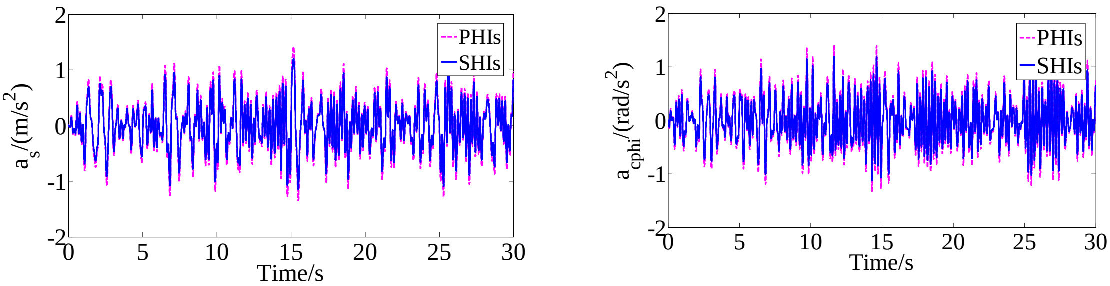
	PVB	NM	NM	NS	NS	ZE	PS	PM	NVB	ZE

IV. RESULTS AND DISCUSSION

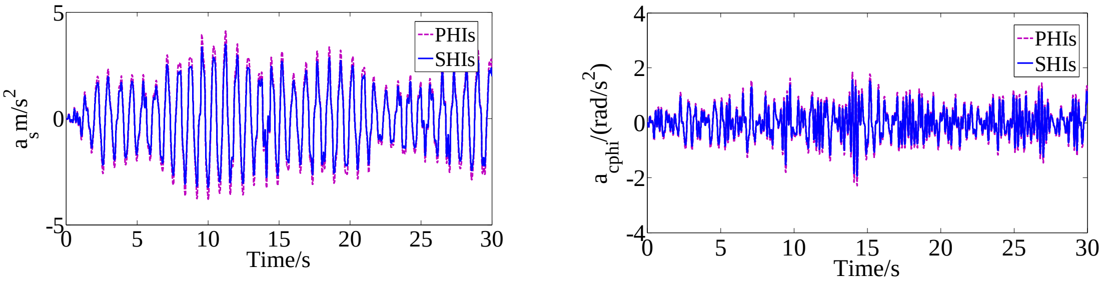
In order to solve the equations of motion of the vehicle dynamics system on section 2and design the fuzzy logic controller (FLC) for control SHIs, Matlab/Simulink environment software is used to simulate and control with a set of parameters of the vehicle in the references [8-11]. The results of the time domain acceleration response ofthe vertical driver's seatand cab's pitch angle with SHIs compared to PHIs when vehicle on the poor groundsurface condition (ISO class D) at v=10 km/h and empty load are shown in Fig.2.From the achieved results in Fig.2, we show that the peak amplitude values of a_s and a_{cphi} with SHIS respectively significantly reduce compared to PHIs which indicates that the efficiency of the fuzzy logic controller has greatly improved the ride comfort of vehicle under large amplitude and low frequency excitations of ground surface.



(a) Vertical driver's seat (b) Pitching angle of cab

Fig. 1. The results of the time domain acceleration response of the vertical driver's seat and cab's pitch angle with SHIs compared to PHIs when vehicle on the poor ground surface condition (ISO class D) at v=10 km/h and empty load

The vehicle moving speed increases: the results of the time domain acceleration response ofthe vertical driver's seatand cab's pitch angle with SHIs compared to PHIs when vehicle on the poor groundsurface condition (ISO class D) at v=15 km/h and empty load are shown in Fig.2. From the achieved results in Fig.3, we show that the peak amplitude values of a_s and a_{cphi} with SHIS respectively significantly reduce compared to PHIs. However, that the peak amplitude values of a_s and a_{cphi}increase very quickly when the vehicle moving speed increases.



(a) Vertical driver's seat (b) Pitching angle of cab

Figure 3. The results of the time domain acceleration response of the vertical driver's seat and cab's pitch angle with SHIs compared to PHIs when vehicle on the poor ground surface condition (ISO class D) at v=15 km/h and empty load

V. CONCLUSION

In this study, a half- vehicle dynamic model ofa wheel loader is proposed to analyzethe ride comfort performance of SHIs compared with that of PHIsunder two survey conditions.Fuzzy logic controller is designed for control of the damping coefficient of a SHIs for a wheel loader.Some conclusions can be drawn from the results of the analysis:(1) that the peak amplitude values of a_s and a_{cphi} with SHIs respectively significantly reduce compared to PHIs which indicates that the efficiency of the fuzzy logic controller has greatly improved the ride comfort of vehicle under large amplitude and low frequency excitations of ground surface; (2) The peak amplitude values of a_s and a_{cphi}increase very quickly when the vehicle moving speed increases.The study results are the theoretical basis for optimal design and optimal control for SHIs of wheel loader cab.

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